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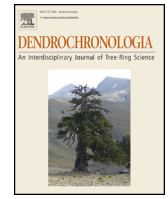

Blue intensity as a temperature proxy in the eastern United States: A pilot study from a southern disjunct population of *Picea rubens* (Sarg.)

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ABSTRACT

Annual surface air temperatures across the eastern United States (US) have increased by more than 1 °C within the last century, with the recent decades marked by an unprecedented warming trend. Tree-rings have long been used as a proxy for climate reconstruction, but few truly temperature-sensitive trees have been documented for the eastern US, much less the Appalachian Mountains in the Southeast. Here, we measure blue intensity (BI) and ring width (RWI) in red spruce growing at the southernmost latitudinal range margin of the species on the North Carolina-Tennessee border to test the efficacy of using either metric as a temperature proxy in the eastern US. The BI and RWI chronologies spanned 1883–2008 and had an interseries correlations of 0.42 and 0.54, respectively, but time series were trimmed to the period 1950–2008 due to low sample depth. We discovered strong, positive, and stable correlations between both current-year early fall (September–October) T_{max} (r = 0.62; p < 0.001) and T_{mean} (r = 0.51; p < 0.001) and ΔBI during the period 1950–2008, but found no significant relationships between temperature and RWI. We show BI metrics measured in red spruce to be a promising temperature proxy for the southern Appalachian Mountain region. Future research should focus on testing [1] the efficacy of using BI on red spruce collected from across the species range, and [2] the potential for using BI as a temperature proxy in other conifers distributed in the eastern US.

1. Introduction

Anthropogenic activities are the foremost contributors to the increasing severity of global climate variability. Notably, annual surface air temperatures across the eastern United States (US) have increased by more than 1 °C within the last century (IPCC, 2014). This warming trend is expected to continue, increasing surface air temperatures across the southern Appalachian Mountains and Southeast US by at least 2.5 °C within the next century (Kunkel et al., 2013; Horton, 2014). Tree-rings have long been used as a proxy dataset for climate reconstruction. However, there are few reported tree-ring proxies of temperature in the eastern US (*e.g.* Cook and Johnson 1989; Pearl et al., 2017), and none for the Southeast. Red spruce (*Picea rubens* Sarg.) is a common conifer species in the eastern US, with a core distribution in the northeastern US and Canada, and small, disjunct populations extending down to the highest-elevations of the southern Appalachian Mountains on the North Carolina-Tennessee border. These low-latitude, disjunct populations of climate refugia species left over after the last glacial period—such as red spruce—could be critically important for providing an historical context for past temperatures.

In recent years, Blue Intensity (BI) metrics have been refined and increasingly integrated into the field of dendroclimatology (McCarroll et al., 2002; Björklund et al., 2014; Rydval et al., 2014; Wilson et al., 2014; Dolgova, 2016). However, most BI studies are focused on high-latitude species. In the northeastern US, maximum latewood density (MXD) was used successfully to reconstruct summer monthly temperatures (Conkey, 1986; Briffa et al., 1992). Delta BI (ΔBI; the difference of latewood BI and earlywood BI, which has comparable temperature correlations to MXD (*e.g.* Björklund et al., 2015), offers an efficient and cost-effective alternative for reconstructing temperature. To date, no BI-derived temperature proxies have been explored for the eastern US. In this paper, we demonstrate successful use of ΔBI as a temperature proxy using red spruce growing at the southern range limit for the species. Given the extensive distribution of red spruce from North Carolina/Tennessee into Canada, we highlight the potential of using BI techniques to produce temperature reconstructions across the eastern US (Fig. 1).

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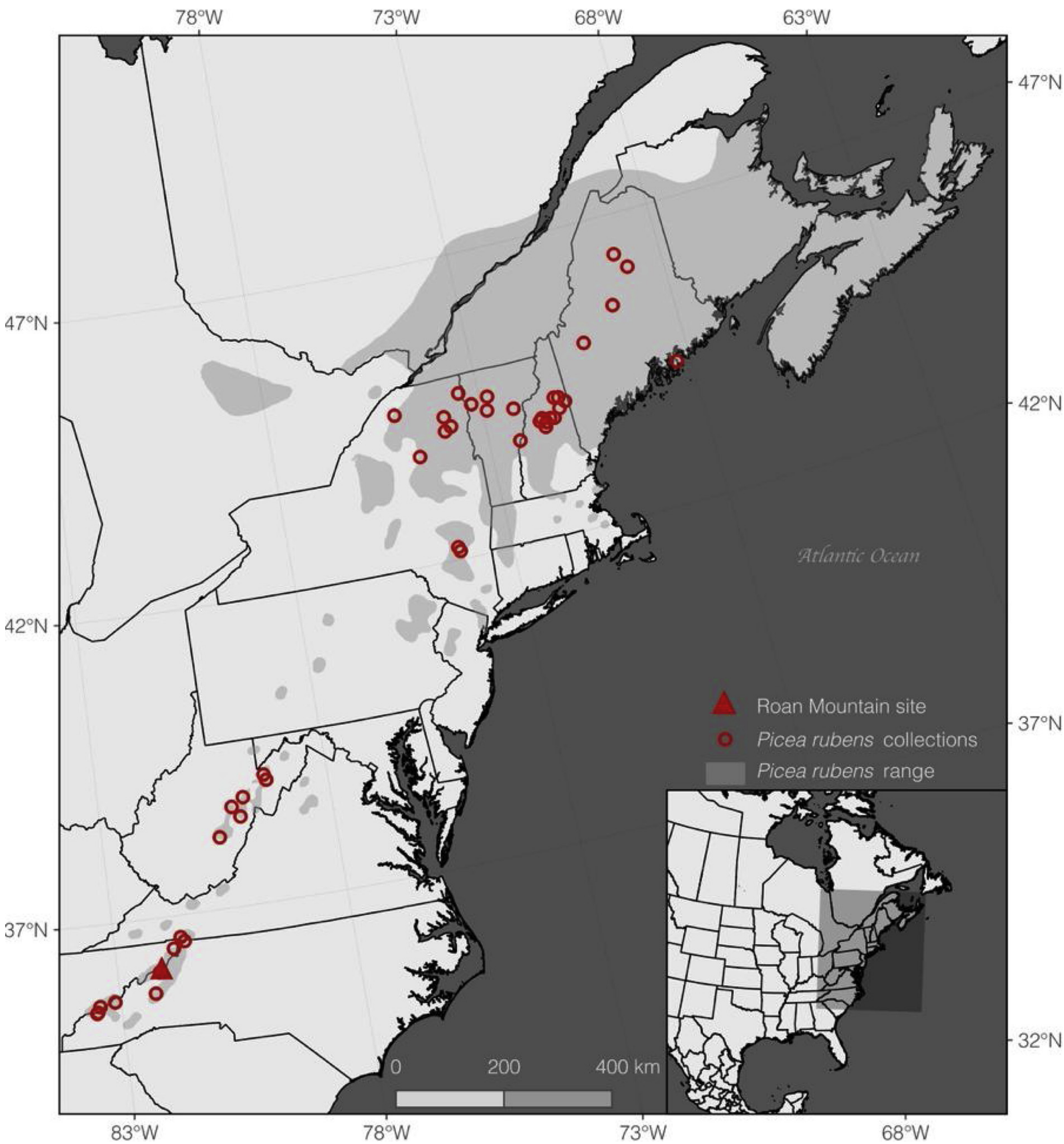

Fig. 1. Historical range (gray polygon; Little, 1971) of red spruce (*Picea rubens* Sarg.) in North America shown with the location of the Roan Mountain, North Carolina/Tennessee, USA study site (this study; triangle) and previously-documented locations of red spruce tree-ring collections (circles) in the literature and/or on the International Tree Ring Data Bank.

2. Methods

2.1. Study area

Tree-ring samples for this study were collected from Roan Mountain, North Carolina/Tennessee, US (36.10 °N, 82.13 °W; Fig. 1). The Roan Mountain area covers approximately 19 km^2 of the southern Appalachian Mountains and is located in the Blue Ridge physiographic province. Roan Mountain elevation ranges between 786 and 1916 m, and the area is classified as Cfb (marine temperate climate) under the Köppen climate classification system (White et al., 2012). Soils are well-drained Inceptisol loams that form on steep, rocky slopes and ridge tops (NRCS 2010). Overstory species composition is heavily dominated by red spruce and Fraser fir (*Abies fraseri* (Pursh) Poir.), with notable presence of associate species such as yellow birch (*Betula alleghaniensis* Britt.), mountain maple (*Acer spicatum* Lam.), and American beech (*Fagus grandifolia* Ehrh.) (White et al., 2012).

2.2. Sample selection

In 2008, increment cores were collected from red spruce within six high elevation (> 1800 m) circular 0.05 ha fixed-radius (12.66 m) plots (separated by at least 100 m) as part of a study detailed in White et al. (2012). All plots were downslope from the ridgeline and predominately on the south-eastern aspect. Samples were collected as close to the root-shoot interface to obtain the maximum amount of growth rings for each individual (Fritts, 1976). For the purposes of this study, we selected increment cores from White et al. (2012) that [1] derived from canopy

dominant trees, [2] contained the greatest number of growth rings, and [3] exhibited minimal disturbance trends in ring-width patterns.

2.3. Chronology development

Red spruce cores were first mounted, then progressively sanded to 1000 grit (Speer 2010). We scanned all samples at 2400 dpi on an Epson Expression XL 12,000 scanner using an IT8.7/2 calibration card coupled with 89 Silverfast software to ensure reproducibility. After calibration, we delineated rings and obtained ring-width (RWI) and ΔBI data using CooRecorder (Larsson, 2013). Although we investigated multiple BI metrics (*i.e.*earlywood maximum reflectance, latewood minimum reflectance (LWBI)), we used the ΔBI metric because it greatly reduces the inherent bias of BI data resultant from potential inter-ring discoloration (Björklund et al., 2013).

All samples were crossdated visually, then checked using the software COFECHA (Holmes, 1983). After examining the effects of both the age-dependent and 2/3 spline interactive detrending approaches, we ultimately detrended both the red spruce RWI and ΔBI series using the Signal-Free (SF) detrending approach (Melvin and Briffa, 2008) with a 2/3 spline to produce chronologies with less bias in the mid-lower frequencies. Because the increment cores selected for analysis were of similar age, the 2/3 spline proved a better fit compared to the age-dependent spline. Further, initial climate-growth correlation tests with both the 2/3 and age-dependent spline chronologies revealed similar but stronger agreement between temperature data and the 2/3 spline chronology. We used the expressed population statistic (EPS) to assess the signal strength of all detrended series.

2.4. Climate analysis

We tested Pearson correlation coefficients between the RWI and ΔBI and temperature datasets temporally using the TreeClim package in R (R.C. Team, 2013; Zang and Biondi, 2015) and spatially using the KNMI Climate Explorer (Royal Netherlands Meteorological Institute, 2016; Trouet and van Oldenborgh, 2013). We performed our statistical tests using mean (T_{mean}) and maximum (T_{max}) monthly temperatures from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly et al., 1994) surface temperature dataset at 4k resolution and taken from the Roan Mountain region (36.21–35.17 °N, 82.09–81.05 °W). Correlations were calculated over the 1950–2008 period based on the low sample depth and EPS prior to 1950. We used TreeClim to test for signal stability using forward moving interval correlation analysis (*c.f.* Saladyga and Maxwell, 2015).

3. Results

We selected 52 red spruce increment cores out of the 286 total cores collected by White et al. (2012) based on the radial growth parameters provided in the Methods section. The ΔBI chronology spanned the period 1883–2008 and had an interseries correlation of 0.42. However, sample depth and thus EPS dropped below 0.85 at the year 1949, so the final ΔBI time series used for analyses spanned 1950–2008 (Fig. 2A). The RWI chronology spanned 1883–2008 with an intersersies correlation was 0.54. and had an EPS value of ≥ 0.85 during the period 1904–2008. For comparison purposes, we used the common period of both chronologies, 1950–2008, for subsequent analyses.

We tested a number of BI metrics and discovered the strongest correlations between the temperature data and ΔBI. We found current-year early fall (September–October) T_{max} ($r = 0.62$; $p < 0.001$) and T_{mean} ($r = 0.51$; $p < 0.001$) were positively correlated with ΔBI during the period 1950–2008 (Fig. 2A; results for T_{mean} not shown). We also found strong agreement between LWBI and Sep–Oct T_{max} ($r = 0.51$; $p < 0.001$) and T_{mean} ($r = 0.54$; $p < 0.001$). Agreement between ΔBI and both T_{max} ($r = 0.11$; $p > 0.10$) and T_{mean} ($r = 0.10$; $p > 0.10$) dropped significantly prior to 1950 due to a decrease in the number of samples. Temporally, the stability of the ΔBI-T_{max} and ΔBI-T_{mean} relationships were strong for the months of September and October from 1950 to 2008 (only T_{max} shown Fig. 2B). Spatially, Sept–Oct T_{max} showed the highest seasonal correlation values ($r > 0.60$), as we found Roan Mountain red spruce to be spatially representative of maximum temperature centralized along the southern Ridge and Valley and Blue Ridge provinces and extending north through the Piedmont and Appalachian Plateau to the Adirondack Mountains (Fig. 2C). Our analysis showed no significant correlations between RWI and T_{max} ($r = 0.11$; $p > 0.10$) or T_{mean} ($r = 0.02$; $p > 0.10$) (for comparison, RWI-T_{max} shown in Fig. 2D).

4. Discussion

In the context of impending temperature increase during the next few decades, tree-ring based reconstructions—which provide valuable information about regional to hemispheric climate history—allow for a better understanding of climate variability over time and enable us to place the current warming trend into historical context. Our study shows BI analysis performed on red spruce growing on Roan Mountain, North Carolina/Tennessee to be a viable method for assessing temperature variability for the southern Appalachian Mountain region. As a result of the logging legacy visible through much of the Appalachian region (*i.e.* White and Cogbill, 1992), our sample population was young, even-aged, and overall limited by a lack of older individuals (*e.g.* > 60 years). This demonstrated that generally, more BI samples are needed to carry the overall population signal compared to RWI (*c.f.* Rydval et al., 2014; Wilson et al., 2014). Hence, over-sampling and targeting older individuals is a practice that should be noted as application of BI extends throughout the eastern US.

To our knowledge, this study is the first to formally document the efficacy of using ΔBI as a temperature proxy in the eastern US. Our results suggest that ΔBI has a strong relationship with instrumental temperature data compared to RWI, and thus should be investigated elsewhere in viable conifers across the eastern US. Previous studies correlating RWI and temperature in the eastern US (*e.g.* McLaughlin et al., 1987; Johnson et al., 1988; Webster et al., 2004) have related unstable climate-growth relationships to the dendroecology and decline of red spruce throughout its range, and Roan Mountain red spruce shows similar results. Yet, Pearl et al. (2017) provide a robust and skillful temperature reconstruction for the northeast US using RWI of Atlantic white cedar (*Chamaecyparis thyoides* L.), which like red spruce, exhibits a unique distribution characterized by range disjunctions and climate refugia.

For red spruce, RWI is likely more heavily influenced by residual signal noise from ecological disturbances (*e.g.* White et al., 2012;2014), and therefore, requires more vigorous detrending methods (*e.g.* Cook and Jacoby 1977; Conkey 1979; Pederson et al. 2004) than ΔBI data. White et al. (2014) observed a general decline in red spruce RWI from the Roan Mountain site starting in the 1960s and continuing until *ca.* 1990. They attributed the decline in RWI to the possible effects of acid deposition, which has been shown to be a potential contributor to overall red spruce decline throughout the region (*e.g.* Johnson and Siccama, 1983; Adams and Eagar, 1992; Soulé, 2011). We did not observe this apparent decreasing trend in ΔBI as reported for RWI by White et al. (2014).

Because we performed our study on individuals located at the southern range limit for red spruce, similar if not stronger results should be found within higher-latitude portions of the range. Further, future investigations should focus on testing the efficacy of using other conifer species distributed across the eastern US for a temperature signal *via* BI. Yet, discoloration (*e.g.* resin pocket, blue stain *e.g. Grosmannia clavigera*) is one of the greatest sources of bias and error in BI analysis (Rydval et al., 2014). We observed a lack of visual pigment variation between the heartwood and sapwood in red spruce collected from the Roan Mountain site. Additionally, we observed an overall absence of

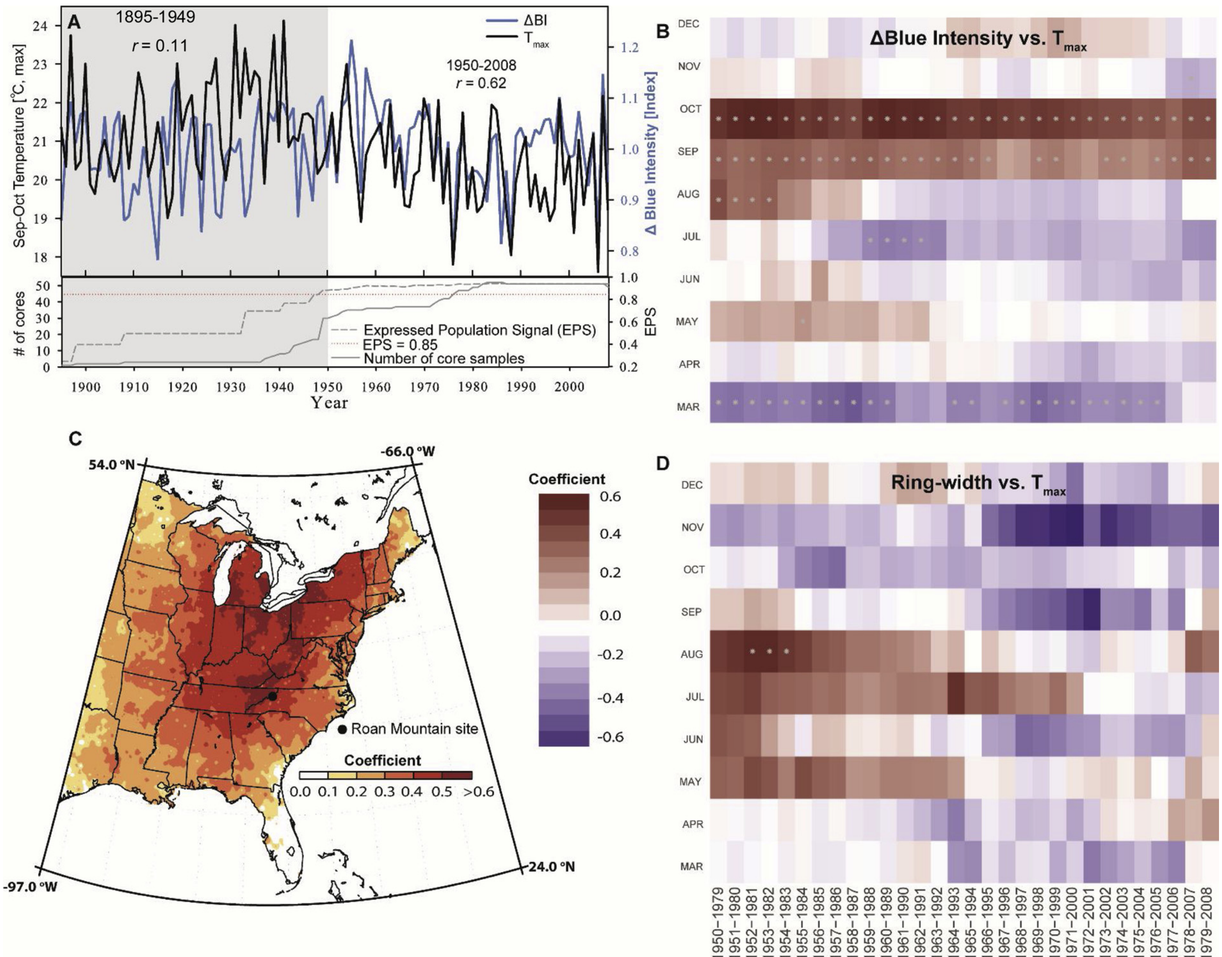

Fig. 2. (A) Relationship between the red spruce (*Picea rubens* Sarg.) delta blue intensity (ΔBI) chronology (blue) from Roan Mountain, North Carolina/Tennessee (n = 52) and 4k PRISM Sept–Oct maximum temperature (T_{max}; °C; black) values taken from the region: 36.21–35.17 °N, 82.09–81.05 °W during the period 1950–2008. (B) Forward moving monthly correlations during the 1950–2008 period between the ΔBI chronology and Sep–Oct T_{max}. (C) Spatial correlations between gridded 4k PRISM Sept–Oct T_{max} during the period 1950–2008 and ΔBI. (D) Forward moving monthly correlations during the period 1950–2008 between RWI and Sep–Oct T_{max}.

discoloring resins in cores. This combination of favorable wood characteristics ultimately allowed us to analyze our cores without the need of any color-removing sample preparation such as ethanol or acetone treatments (Rydval et al., 2014), but this might not be the case with other conifers tested in the eastern US.

Although our overall ΔBI chronology was short and did not extend beyond the observed period (*ca.* 1895), we demonstrate the potential to extend the BI network throughout other portions of the species range (Fig. 1) using extant collections. Numerous red spruce chronologies on the International Tree Ring Data Bank, many of which extend back to the 16th century, may prove valuable for reconstruction models. Future research should focus on filling the spatial gaps in temperature proxies throughout the eastern US by testing [1] the efficacy of using ΔBI on red spruce collected from throughout the species range, and [2] the potential for using ΔBI, or other BI metrics (*e.g.* LWBI, earlywood maximum reflectance), as a temperature proxy in other conifers, such as *e.g.* Fraser fir, eastern hemlock (*Tsuga canadensis*), Carolina hemlock (*Tsuga caroliniana*), Atlantic white cedar (*e.g.* Pearl et al. 2014), black spruce (*Picea mariana*), and balsam fir (*Abies balsamea*).

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